DESIGN OF WASTE HEAT RECOVERY SYSTEM IN A SPONGE IRON PLANT

A thesis submitted in partial fulfillment of the Requirements for the degree of Bachelor of Technology

In

Chemical Engineering

by

Saurav Kumar Sahu
Roll No. 107CH031

Under the guidance of
Dr. Shabina Khanam

DEPARTMENT OF CHEMICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA
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CERTIFICATE

This is to certify that the thesis entitled "Design of Waste Heat Recovery System in A Sponge Iron Plant" being submitted by Saurav Kumar Sahu as an academic project in the Department of Chemical Engineering, National Institute of Technology, Rourkela is a record of bonafide work carried out by him under my guidance and supervision.

Place:

Date:

Prof.Shabina Khanam
Assistant Professor
Dept. of Chemical Engineering,
NIT Rourkela

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Saurav Kumar Sahu

107CH031

ABSTRACT

India is emerging as the leading producer of sponge iron among developing as well industrially developed nations. Sponge iron is produced by direct reduction of iron ore (DRI process) and is popular because of use of non-coking coal. The conventional blast furnace process uses coking coal. The DRI process doesn't require coking coal and therefore is advantageous.

In the present work waste heat recovery system is designed to integrate the heat of waste gas in the sponge iron process. For this purpose a case study of typical sponge iron production process is considered. The waste gas from a sponge iron plant exits at a temperature of around 200-300°C. A lot of sensible heat is lost with these gases. This heat is utilized to preheat the air entering to kiln. Further, the waste gas at reduced temperature is used to cool hot sponge iron which is previously carried out by water. Consequently, considerable energy and water savings is achived which increases the efficiency of the process manifold. The objective of this project is to design a suitable heat recovery system for above cases which can efficiently remove the sensible heat and put it to use.

The annual savings upon installing this system was found to be around Rs.95.3 lakh. The annual coal savings was calculated to be 620 tons, which is worth Rs.15.5 Lakh. The annual water savings was calculated to be 1.2 million tonnes, which is worth Rs.83 Lakhs.

Keywords: Waste Heat, Recovery, Waste Heat Utilisation, Design

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CHAPTER 1

INTRODUCTION

Sponge iron is the metallic form of iron produced from reduction of iron oxide below the fusion temperature of iron ore (1535 ^{o}C) by utilizing hydrocarbon gases or carbonaceous fuels as coal. The reduced product having high degree of metallisation exhibits a 'honeycomb structure', due to which it is named as sponge iron. As the iron ore is in direct contact with the reducing agent throughout the reduction process, it is often termed as direct reduced iron (DRI). Sponge iron is produced primarily both by using non-coking coal and natural gas as reductant and therefore classified as coal based and gas based process respectively. Due to a promising availability of coal, the coal based sponge iron plants share the major amount of its production. At present, there are 118 large and small sponge iron plants operating in India, amongst them only 3 are natural gas based and the remaining 115 plants are coal based.

With the availability of raw materials, high demand of sponge iron and less payback period, sponge iron industry has emerged as a profitable venture. However, due to lack of proper integration techniques, non-optimal process parameters, high energy consumption and old running process technology, the industry are facing a setback in market. Further, it is seen that much of the heat generated in the process is lost without being recovered due to lack of heat recovery options. Thus the energy conservation in sponge iron plants has also sought the attention of many investigators. Eriksson et al studied on the energy survey of sponge iron process and showed that the process is 40% energy efficient and the major loss is through exhaust gases [6]. Energy efficiency is defined as the energy needed for the reduction reactions compared to the energy added to the system. Biswas et al. found that 10-12 % energy can be saved by controlled axial and radial air injection, leading to efficient combustion and improved heat transfer thus reducing waste gas temperatures [2]. Jena et al. worked on the kiln data at the production capacity of 350 tpd, OSIL and showed that the thermal efficiency of the process is 51.315% [7]. Considerable amount of heat is lost in the waste gas which is about 33% of the heat generated in the kiln. The above fact has also been reiterated by many other investigators [1],[5].

Moreover, waste heat recovery systems developed in the past depend on the quality of heat which is mainly temperature of the waste streams. Waste heat boilers have been successfully installed and used in different industries. They work on the principle of Steam-Rankine Cycle. Installation of waste heat boilers needs high quality heat sources. The temperature of the waste stream needs to be around 600℃. For low temperature heat sources, Organic-Rankine cycle based Power generation systems have been developed. These require a source temperature of around 70℃. In European countries, building heating systems have been developed based on waste heat from household and industrial sources. Other waste heat utilisation systems include Absorption/Adsorption refrigeration systems.

All the above mentioned systems have got inefficiencies and may not be applicable to sponge-iron industries. Steam Rankine cycle needs high temperature sources. In a sponge iron plant, high temperature waste sources are unavailable and therefore this system can't be applied here. Organic Rankine cycle is based boiler is costly and inefficient. The source temperature requirement of 70℃ renders this system unfit for the current system. Other systems like Absorption/Adsorption refrigeration systems have been tested. These systems, being costly and having large payback period, are not suitable for small scale plants. Therefore, the conventional heat recovery systems can't be applied to sponge iron plants.

Based on above discussion it is found that a fresh look is required on sponge iron process to propose the new design with integration of energy. For this purpose following objectives are to be achieved:

1. To identify the possible areas of sponge iron process where energy is available and can be utilized in the process.
2. To design suitable waste heat recovery systems for sponge iron process using the possible areas
3. To perform economic analysis of the modified design for sponge iron process based on capital investment, coal consumption, water requirement, energy consumption, total profit, payback period, etc.

CHAPTER 2

LITERATURE REVIEW

2.1 DRI PROCESS OF SPONGE IRON MAKING

2.1.1 Introduction

Direct Reduced Iron, also called Sponge Iron, is produced by direct reduction of iron ore by a reducing gas produced from coal or natural gas. This gas is mainly Carbon Monoxide gas. The process is known as direct reduction because iron ore is reduced in solid state itself. Iron ore doesn't melt [13]. The conventional route for making steel consists of sintering or pelletization plants, coke ovens, blast furnaces, and basic oxygen furnaces. Such plants require high capital expenses and raw materials of stringent specifications. Coking coal is needed to make a coke strong enough to support the burden in the blast furnace. Integrated steel plants of less than one million tons annual capacity are generally not economically viable. The coke ovens and sintering plants in an integrated steel plant are polluting and expensive units.Direct reduction, an alternative route of iron making, has been developed to overcome some of these difficulties of conventional blast furnaces. DRI is successfully manufactured in various parts of the world through either natural gas or coal-based technology. Iron ore is reduced in solid state at 800 to 1,050 °C (1,472 to 1,922 °F) either by reducing gas (H_2+CO) or coal. The specific investment and operating costs of direct reduction plants are low compared to integrated steel plants and are more suitable for many developing countries where supplies of coking coal are limited.

2.1.2 Raw Materials

The raw material and its sizes used for sponge iron process are shown in Table 2.1.

Table 2.1: Raw Materials for Rotary Kiln

Material	**Type**
Iron-Ore	5-18 mm
Coal	3-20 mm
Dolomite	2-06 mm
Air	-

2.1.3 Theory

The theory of Direct Reduction process is very similar to the conventional process. Carbon from coal is partially oxidised to Carbon Monoxide. Carbon Monoxide then reduces Iron ore to produce Iron. The reactions can be shown as:

$$2C + O2 \rightarrow 2CO + heat$$

$$Fe2O3 + 3CO \rightarrow 2Fe + 3CO2 - Heat$$

2.1.4 Commercial Processes:

The important commercial processes available are:- SL/RN, Codir, Accar, TDR & Jindal [3]. These are discussed in the following paragraphs.

2.1.4.1 <u>SL/RN Process</u>

- Iron ore, coal and dolomite are sized and screened to have a proper size.The raw materials are charged into the rotary kiln with the help of conveyor.

- Compressed air is injected into the rotary kiln at various places with the help of blowers. Dampers are used to control the flow rate of air.
- Half of the coal is charged with iron ore charge. After coming in contact with air, it produces CO n CO_2 gases. The exothermic reactions increase temperature of coal and bring it to reaction temperature. The rest of the coal is charged from the discharge end. This reacts with CO_2 to produce CO which acts as the reducing agent for Iron Ore. Iron and CO_2 are progressively formed.The rotary kiln is kept at a slant of 5°-6° which causes the materials to flow under gravity.
- Limestone and dolomite are added as fluxing agents which react with the gangue materials to produce slag.
- The residence time of iron ore inside the kiln is about 10 hours. During this time, iron ore is optimally reduced. Hot sponge iron along with semi burnt coal is discharged at the discharge end. After being discharged, the materials enter a rotary cooler where water is sprayed over the cooler and the temperature is brought down to about 120℃.
- The products, after cooling, need to be separated into Iron, char and other non-magnetic impurities. The iron particles are separated from char and other non-magnetic impurities using electromagnetic separation.
- The products are screened into different sizes and sent to storage. The gases out of the rotary kiln are burnt in a chamber to ensure that CO is negligibly present. The gases, at a temperature of 1000℃, enter the waste heat boiler and then ESP from where they are routed to the stack at a temperature of 200-250℃.

The Flow-Sheet for SL/RN Process is shown in figure 2.1 [20]

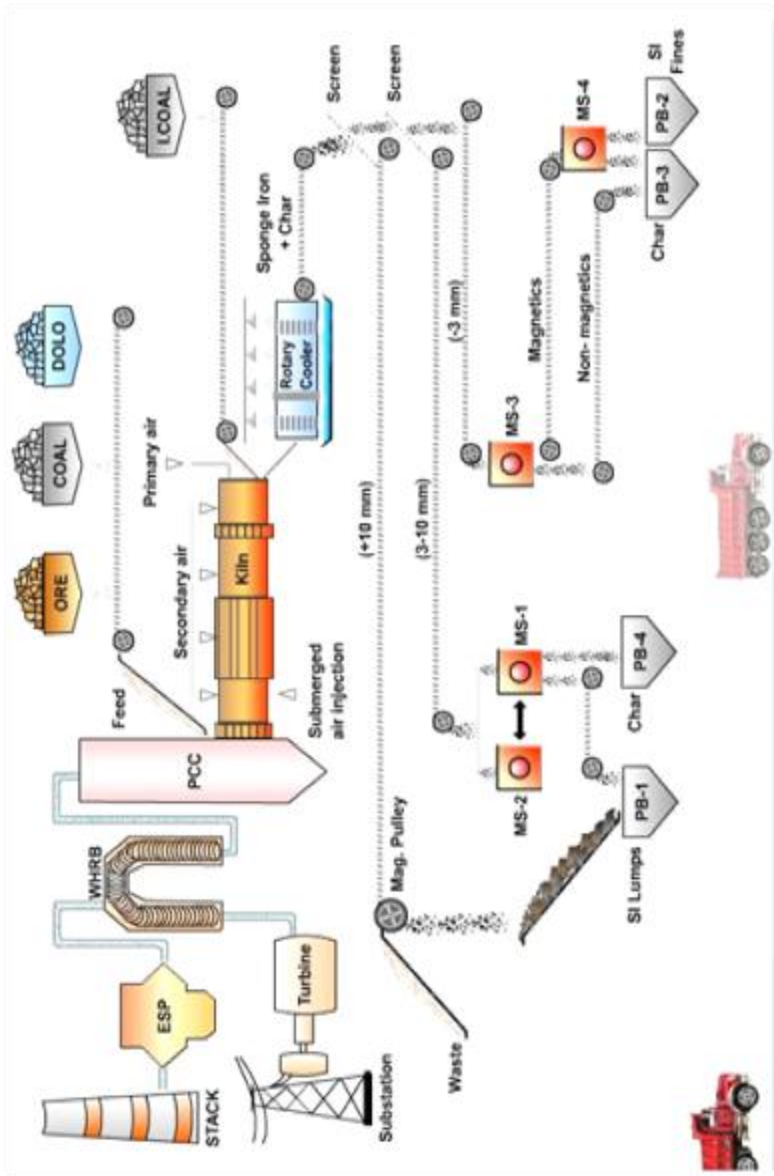

Fig. 2.1:- Flow Sheet of SL/RN Process

2.1.4.2 Codir Process

- Codir stands for Coal Ore Direct Reduction process
- It is very similar to SL/RN Process with minor modifications.
- The coal size range is very coarse, which is a unique feature of Codir (5-35mm). Coal is counter-currently injected into the rotary kiln.
- The air inlets are positioned towards the inlet end of rotary kiln.
- Codir coolers use direct mist of water inside the cooler.

2.1.4.3 Accar

- This stands for Allis-Chalmers Controlled Atmospheric Reduction.
- The process is similar to Sl/Rn & Codir Process.
- The fundamental difference is that, the reductant used in this case is a mixture of coal+ oil or coal+ natural gas.
- Oil/gas is injected directed in radial ports, symmetrically arranged in equally spaced rows.
- The injection is maintained in such a manner that, when the ports are under charge, oil/gas is injected and when the ports are over the bed, air is injected.
- The advantages are higher carbon content, high degree of metallisation, lower energy consumption, lower operating temperatures etc.

2.1.4.4 TDR Process

- This stands for TISCO Direct Reduction process and was developed in India.
- Only Non-Coking coal is used and reductant and fuel oil is used only for kiln preheating.

- Coal used is of a specified size range and injected from both sides.
- Dolomite is used in a specific size range.
- Provision for radial and axial injection of air exists.
- Rotary kiln has a diameter of 3.75 m and length of 72m. inclination is 1.432˚.

2.1.4.5 Jindal

- This process was developed by Jindal Strips Ltd.
- The unique feature is that 55-60% coal is injected from discharge end and rest with ore injection.
- The C/Fe ration is around 0.42-0.44.
- Coal up to 30% ash content is successfully used.
- Blast furnace gas has been used in this process and has resulted in better reduction.
- Steam is produced by utilisation of waste heat.
- The Char and coal washery rejects are used in fluidised bed combustion boiler and results in better waste heat recovery.

2.1.5 Advantages of DRI process:

- The energy requirements of a sponge iron plant are much lesser than conventional Blast Furnace plants.
- The process doesn't require coking coal or coke.
- The product Hot Briquetted iron is a compact form of DRI designed for ease of transportation.
- The percentage of iron is generally more than pig iron.

- The operating costs are low too.

2.2 WASTE HEAT RECOVERY

Captured and reused waste heat is an emission free substitute for costly purchased fuels or electricity. Numerous technologies are available for transferring waste heat to a productive end use. No matter, anywhere from 513 quadrillion Btu/yr of waste heat energy remains unrecovered as a consequence of industrial manufacturing. One has to investigate industrial waste heat recovery practices, opportunities, and barriers in order to identify technology research, development, and demonstration (RD&D) needed to enable further recovery of industrial waste heat losses. Key opportunities are available in optimizing existing systems, developing technologies for chemically corrosive systems, recovering heat from non-fluid heat sources, and recovering low temperature waste heat.

Observed trends are:

- Waste heat recovery systems are frequently implemented, but constrained by factors such as temperature limits and costs of recovery equipment.
- Most unrecovered waste heat is at low temperatures.
- There are certain industrial subsectors where heat recovery is less common, due to factors such as heat source's chemical composition and the economies of scale required for recovery.
- Losses from non-traditional waste heat sources are difficult to recover, but significant.

2.2.1 Waste Heat

Waste heat is heat generated in a process by way of fuel combustion or chemical reaction, which is then "dumped" into the environment and not reused for useful and economic purposes. The essential fact is not the amount of heat, but rather its "value". Typical sources of waste heat and recovery options are listed in Table 2.2.

Table 2.2:- Waste Heat Sources and Uses

Waste Heat Sources	Uses for Waste Heat
Combustion Exhausts: Cement kiln Glass melting furnace Aluminum reverberatory furnace Boiler • Process offgases: Steel electric arc furnace Aluminum reverberatory furnace • Cooling water from: Furnaces Air compressors Internal combustion engines • Conductive, convective, and radiative losses from equipment: HallHèroult cells • Conductive, convective, and radiative losses from heated products: Hot cokes Blast furnace slags	• Combustion air preheating • Boiler feedwater preheating • Load preheating • Power generation • Steam generation for use in: power generation mechanical power process steam • Space heating • Water preheating • Transfer to liquid or gaseous process streams

2.2.2 Classification

In considering the potential for heat recovery, it is useful to note all the possibilities, and grade the waste heat in terms of potential value. A number of heat sources and their qualities have been shown in Table 2.3.

Table 2.3:- Grading Of Waste Heat

S.No.	Source	Quality
1.	Heat in flue gases.	The higher the temperature, the greater the potential value for heat recovery
2.	Heat in vapour streams.	As above but when condensed, latent heat also recoverable.
3	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheats.
4.	Heat losses in cooling water.	Low grade – useful gains if heat is exchanged with incoming fresh water.
5.	Heat losses in providing chilled water or in the disposal of chilled water.	a) High grade if it can be utilized to reduce demand for refrigeration. b) Low grade if refrigeration unit used as a form of heat pump.
6.	Heat stored in products leaving the process	Quality depends upon temperature.
7.	Heat in gaseous and liquid effluents leaving process.	Poor if heavily contaminated and thus requiring alloy heat exchanger.

2.2.3 High temperature heat recovery

High temperature heat sources range from 500-1500˚C. Some of the high temperature sources and their respective temperatures have been shown in table 2.4 [18].

Table 2.4:- High Temperatures waste gases

Types of device	Temperature, ^{0}C
Nickel refining furnace	1370 –1650
Aluminium refining furnace	650-760
Zinc refining furnace	760-1100
Steel heating furnaces	925-1050
Cement kiln (Dry process)	620- 730
Hydrogen plants	650-1000
Fume incinerators	650-1450

2.2.4 Medium temperature heat recovery

Medium temperature heat sources have their temperatures in the range of 200-600˚C. A few medium temperature heat sources have been shown in table 2.5 [18].

Table 2.5:-Medium Temperatures waste gases

Type of Device	Temperature, °C
Steam boiler exhausts	230-480
Gas turbine exhausts	370-540
Reciprocating engine exhausts	315-600
Heat treating furnaces	425 – 650
Drying and baking ovens	230 – 600
Catalytic crackers	425 – 650

2.2.5 Low temperature heat recovery

Low temperature heat sources have their temperatures in the range of 30-250˚C. A few low temperature heat sources have been shown in table 2.6 [18].

Table 2.6:-Low Temperature Waste heat

Source	Temperature, ^{o}C
Process steam condensate	55-88
Cooling water from: Furnace doors	 32-55
Bearings	32-88
Welding machines	32-88
Air conditioning and refrigeration condensers	32–43
Hot processed liquids	32-232
Hot processed solids	93-232

2.2.6 Benefits of Waste Heat Recovery

Benefits of 'waste heat recovery' can be broadly classified in two categories:

Direct Benefits:

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.

Indirect Benefits:

a) **Reduction in pollution**: A number of toxic combustible wastes such as carbon monoxide gas, sour gas, etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

b) **Reduction in equipment sizes**: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipment such as fans, stacks, ducts, burners, etc.

c) **Reduction in auxiliary energy consumption**: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc. [18].

2.2.7 Development of a Waste Heat Recovery System

Understanding the process is essential for development of Waste Heat Recovery system. This can be accomplished by reviewing the process flow sheets, layout diagrams, piping isometrics, electrical and instrumentation cable ducting etc. [8],[18].

Detail review of these documents will help in identifying:

a) Sources and uses of waste heat

b) Upset conditions occurring in the plant due to heat recovery

c) Availability of space

d) Any other constraint, such as dew point occurring in an equipment etc.

2.3 WASTE HEAT RECOVERY TECHNOLOGIES

Methods for waste heat recovery include transferring heat between gases and/or liquids (e.g., combustion air preheating and boiler feed-water preheating), transferring heat to the load entering furnaces (e.g., batch/cullet preheating in glass furnaces), generating mechanical and/or electrical power, or using waste heat with a heat pump for heating or cooling facilities. Some of the equipment for the purpose is as follows [8], [18].

2.3.1 Heat Exchangers

Heat exchangers are most commonly used to transfer heat from combustion exhaust gases to combustion air entering the furnace. Since preheated combustion air enters the furnace at a higher temperature, less energy must be supplied by the fuel. Typical technologies used for air preheating include Recuperators, furnace regenerators, burner regenerators, rotary regenerators, and passive air preheaters.

2.3.1.1 Recuperators

Recuperators recover exhaust gas waste heat in medium to high temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant tube burners, and reheat furnaces [14]. Recuperators can be based on radiation, convection, or combinations of both. Recuperators are constructed out of either metallic or ceramic materials. A typical recuperator is shown in Fig.2.2.

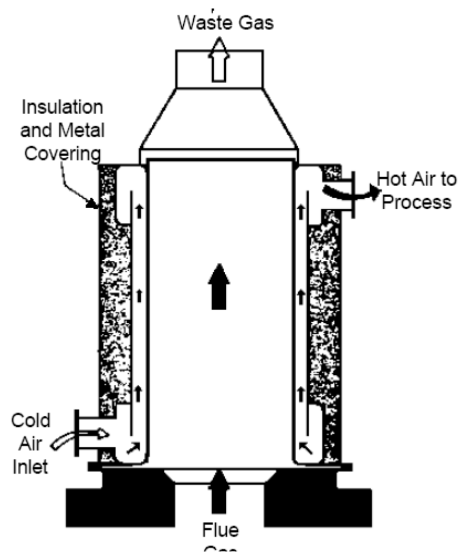

Fig. 2.2:- Metallic Radiation Recuperator

2.3.1.2 Regenerators

The Regeneration which is preferable for large capacities has been very widely used in glass and steel melting furnaces. Important relations exist between the size of the regenerator, time between reversals, thickness of brick, conductivity of brick and heat storage ratio of the brick. A typical Regenerator is shown in Fig 2.3. In a regenerator, the time between the reversals is an important aspect. Long periods would mean higher thermal storage and hence higher cost. Also long periods of reversal result in lower average temperature of preheat and consequently reduce fuel economy.

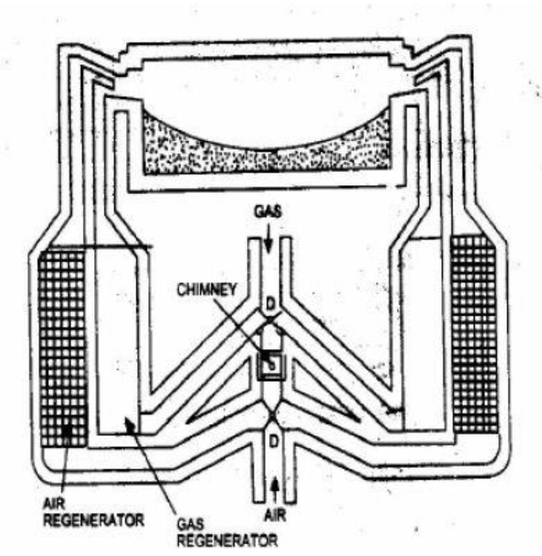

Fig 2.3:- Regenerator

Heat losses from the walls of the regenerator and air in leaks during the gas period and out-leaks during air period also reduces the heat transfer.

2.3.2 Waste Heat Boilers

These are the water tube boilers that use medium to high temperature exhaust gases to generate steam. Waste heat boilers are available in a variety of capacities, allowing for gas intakes from 1000 to1million cu.ft/min. A typical boiler is shown in Fig.2.4. In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output. The steam can be used for process heating or for power generation.

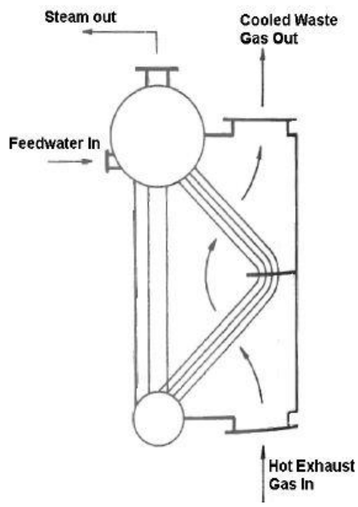

Fig. 2.4: Waste Heat Boiler

2.3.3 Heat Pipe

A heat pipe can transfer up to 100 times more thermal energy than copper, the best known conductor. In other words, heat pipe is a thermal energy absorbing and transferring system and have no moving parts and hence require minimum maintenance. The working of a typical Heat Pipe is shown in figure 2.5.

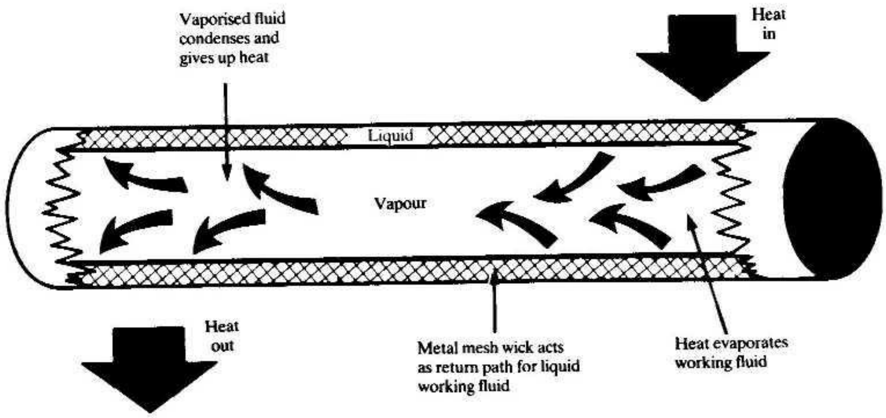

Figure 2.5: Heat Pipe

2.3.5 Factors affecting the waste heat recovery feasibility

Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Important waste stream parameters that must be determined include:

- heat quantity
- heat temperature/quality
- composition
- minimum allowed temperature

- Operating schedules, availability, and other logistics.

These parameters allow for analysis of the quality and quantity of the stream and also provide insight into possible materials/design limitations [18], [(Cook, 1979)].

2.4 UTILISATION OF WASTE HEAT OF FLUE GASES IN SPONGE IRON PLANT

The sponge iron manufacturing process involves reduction of iron ore in a rotary kiln. Coal is used as a fuel and also as reducing agent. Normally, iron ore of 5- 20mm size is mixed with dolomite (limestone) and fed into the rotary kiln at ambient conditions. Coal is used to raise the temperatures of the charge up to 1150℃ in the kiln and further acts as a reducing agent to facilitate chemical reactions involving reduction of iron ore into iron. The reduction process occurs in solid state [below the melting point temperature of iron (1535℃)] and the products formed are in the form of pellets called sponge iron. The entire process is energy intensive with significant quantity of flue gases released from the kiln at around 950℃ temperature.

For sponge iron kilns, particularly of smaller unit capacity below 200 Tons per day (TPD) in India, the waste flue gases are treated in After Burning chamber (ABC) to remove traces of carbon monoxide and then cooled in flue gas cooling system using water and the cooled gases are released into the atmosphere.

For kilns above 200 TPD unit capacities, using the waste heat for power generation technology has been reported in India, and projects were registered as Clean Development Mechanism (CDM) projects. The project activity involves installation of charge pre-heaters to utilize the waste heat energy content of flue gases released during manufacturing process of the sponge iron in rotary kilns. The charge pre-heaters will utilize the sensible heat content of flue gases released at 950℃ from the individual kilns to preheat the incoming raw material i.e. iron ore and dolomite mixture to around 900℃ from ambient temperature of 40℃. The charge pre-heaters are of miniature rotary kiln design to enable adequate mixing of flue gases and raw material mixture for effective heat transfer. Thereafter, the flue gases are released into the atmosphere, complying with the environmental norms. The preheated raw material is then fed to the main rotary kiln for further heating and reduction process to produce sponge iron and hence reduces coal consumption for the same quantity of production. In absence of the project activity, equivalent amount of coal would have been consumed in the main rotary kiln to raise the temperature of the raw material mixture to 900℃. The project activity thus helps in reduction of coal consumption per ton of sponge iron produced in the sponge iron kilns, thus leading to greenhouse gas (GHG) emission reductions.

2.5 CONVENTIONAL METHODS OF HEAT RECOVERY FROM STACK GASES

2.5.1 Feed Water Preheating:

The boiler efficiency can be improved by preheating the make-up water. This make-up water can be heated by using the stack gases which are generally released at around 200℃.In the case of boiler systems, an economizer can be provided to utilize the flue gas heat for pre-heating the boiler feed water. On the other hand, in an air pre-heater, the waste heat is used to heat combustion air. In both the cases, there is a corresponding reduction in the fuel requirements of the boiler. For every 220˚C reduction in flue gas temperature by passing through an economizer or a pre-heater, there is 1% saving of fuel in the boiler. In other words, for every 60˚C rise in feed water temperature through an

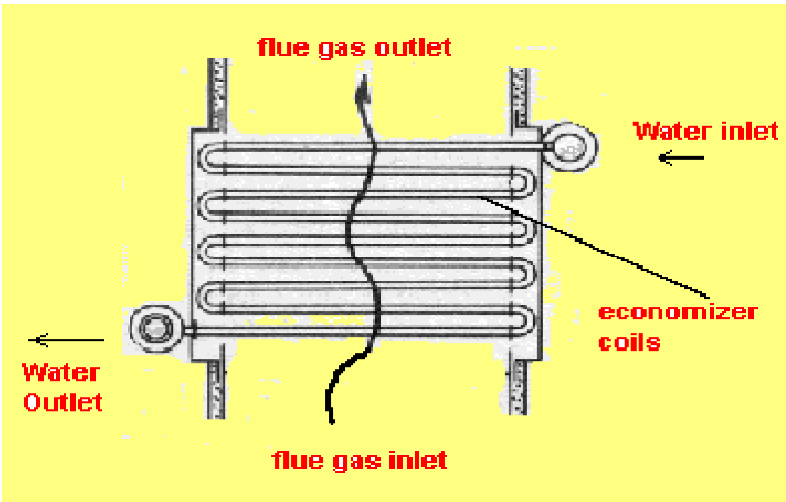

Figure 2.6: Economiser

economizer, or 200˚C rise in combustion air temperature through an air pre-heater, there is 1% saving of fuel in the boiler. A typical economizer is shown in figure 2.6.

2.5.2 Organic Rankine Cycle:

It is one of the methods to convert thermal energy to electrical energy. It is a closed loop system filled with an organic liquid having a low boiling temperature. The Organic Rankine cycle (ORC) is named for its use of an organic, high molecular mass fluid with a liquid-vaporphase change, or boiling point, occurring at a lower temperature than the water-steam phase change. The fluid allows Rankine cycle heat recovery from lower temperature sources such as biomass combustion, industrial waste heat, geothermal heat, solar ponds etc. The low-temperature heat is converted into useful work that can itself be converted into electricity. The working principle of the organic Rankine cycle is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally re-condensed. In the ideal cycle, the expansion is isentropic and the evaporation and condensation processes are isobaric. In the real cycle, the presence of irreversibility lowers the cycle efficiency.

2.5.3 Gas-Gas heat exchangers:

2.5.3.1 <u>Plate Heat Exchanger</u>**:**

The cost of a heat exchange surface is a major cost factor when the temperature differences are not large. One way of meeting this problem is the plate type heat exchanger, which consists of a series of separate parallel plates forming a thin flow pass. Each plate is separated from the next by gaskets and the hot stream passes in parallel through alternative plates whilst the liquid to be heated passes in parallel between the hot plates. To improve heat transfer the plates are corrugated. Hot liquid passing through a bottom port in the head is permitted to pass upwards between every second plate while cold liquid at the top of the head is permitted to pass downwards between the odd plates. When the directions of hot & cold fluids are opposite, the arrangement is described as counter current. A typical plate heat exchanger is shown in the figure 2.7.

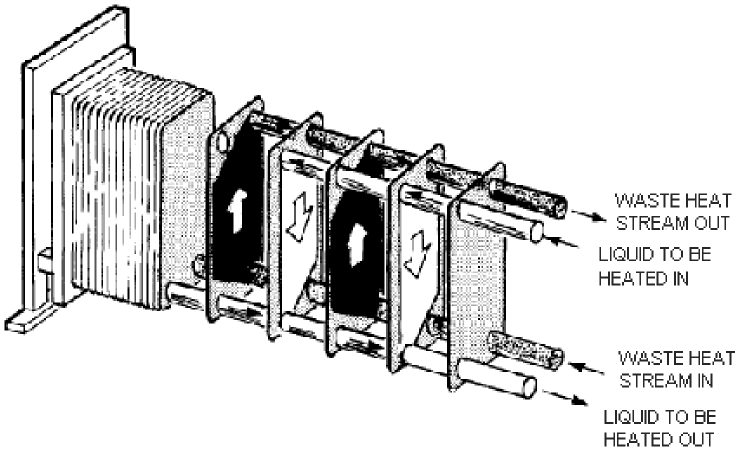

Fig. 2.7:- Plate Heat Exchanger

2.5.4 Direct Contact Heat Exchanger:

Direct contact of a water spray with flue gas turns out to be a rather effective low-energy scrubber.

2.6 POSSIBLE USES OF WASTE HEAT

There are various ways of utilizing waste heat depending on the quality. A few uses have been shown in table 2.7.

Table 2.7:-Uses of Waste Heat

Sl. No.	Possible Uses	Temperature Range (C)
1	Absorption Refrigeration	120-140 degrees steam
2	Adsorption Refrigeration	-do-
3	DeHumidification	Around 80-85 degrees hot water
4	Building Heating	80 - 130 degrees
5	Organic Rankine cycle (power generation)	Around 65 degrees
6	Steam Rankine Cycle (Power Generation)	Around 530 degrees

CHAPTER 3

PROBLEM STATEMENT

3.1 CASE STUDY

The present work is based on the stream data of a typical sponge iron production plant with overall capacity of 200tpd. The following data was collected to carry out the work.

3.1.1 Feed Stream:

The feed mix fed into the rotary kiln is of specific size and composition which is presented in table 3.1. The sources and temperatures of each component have been mentioned too.

Table 3.1: Feed Stream Properties

Raw Material	Source	Particle Size (mm)	Feed Temp(C)	Flow Rate(tph)
Iron Ore	Barbil	5-18	30	6
Coal	M.C.l	<18	30	3.3
Dolomite	Chattisgarh	2-6	30	0.2

3.1.2 Dust Settling Chamber:

The Flue gas enters the dust settling chamber where the dust gets separated. The properties of the gas at inlet and outlet of Dust Settling Chamber are shown in table 3.2.

Table3.2: Gaseous Stream at Dust Settling Chamber

Inlet Temp(C)	Outlet Temp(C)	Flow Rate(tph)	Pressure(mb)
900-950	900-950	25.06	5

3.1.3 After-Burning Chamber:

In the after burning chamber, the residual CO is burnt. The Inlet and outlet temperature of Flue Gas is shown in Table 3.3.

Table 3.3: Gaseous Stream at After Burning Chamber

Inlet Temp(C)	Outlet Temp(C)
900-950	900

3.1.4 Waste Heat Boiler:

The temperature of Flue Gases at the inlet and outlet of boiler is shown in table 3.4.

Table 3.4: Gaseous Stream at Waste Heat Boiler

Inlet Temp (C)	Outlet Temp (C)
900	200

3.1.5 Electrostatic Precipitator:

The temperature of Flue Gases at the inlet and outlet of Electrostatic Precipitator is shown in table 3.5.

Table 3.5: Gaseous Stream at Electrostatic Precipitator

Inlet Temp (C)	Outlet Temp (C)
200-220	130-140

3.2 FLOW SHEET

The flow sheet of the sponge iron production process with material and energy is shown in Figure3.1.

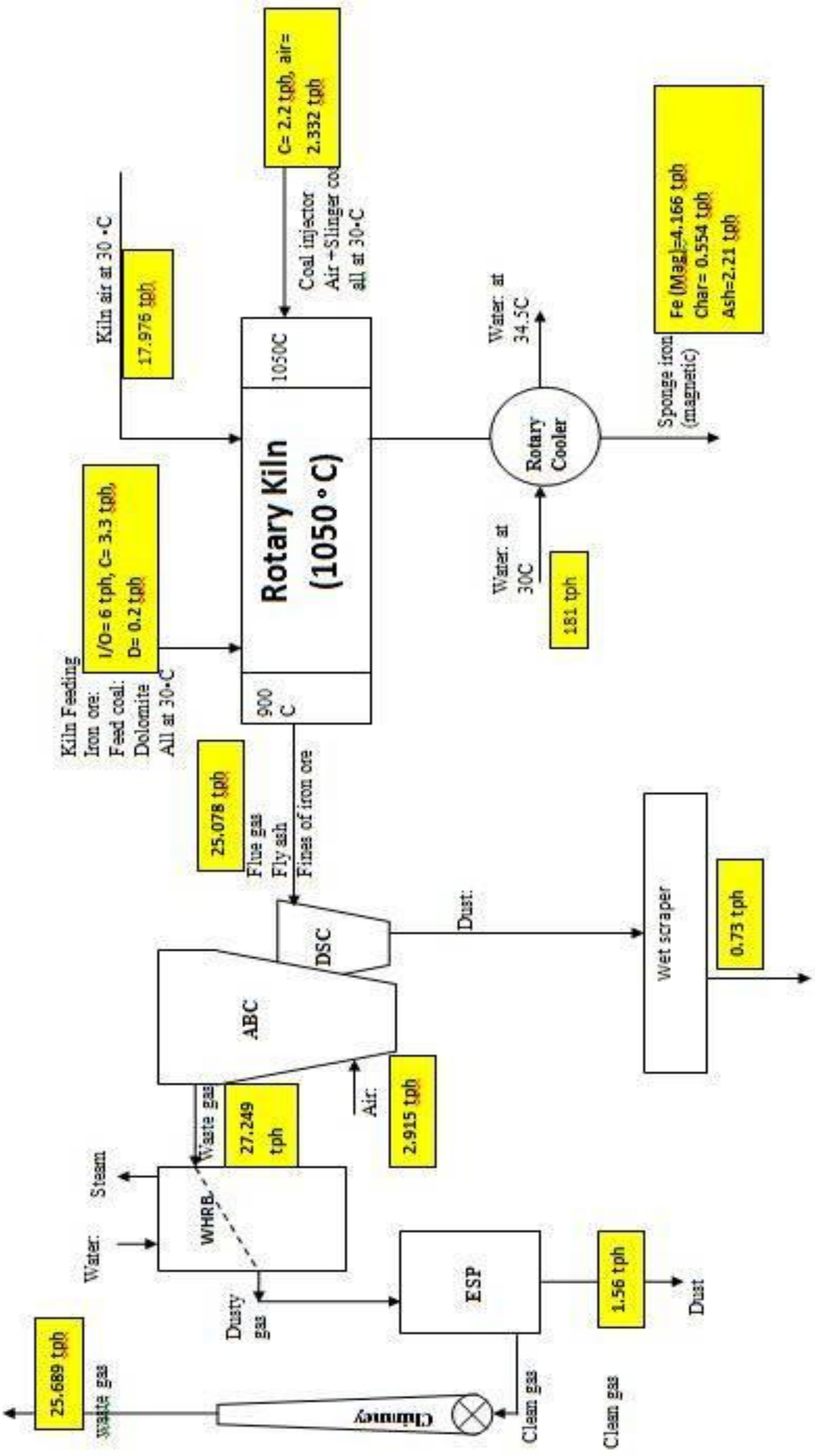

Figure 3.1: Flow Sheet of Typical Sponge Iron Plant

3.2.1 Process description

- Screened Iron ore (6tph), coal(3.3tph) and dolomite(0.2tph) are charged into the rotary kiln with the help of conveyor.
- Compressed air (18 tph) is injected into the rotary kiln at various places with the help of blowers. The temperature is 30˚C.
- Half of the coal is charged with iron ore charge. After coming in contact with air, it produces CO n CO_2 gases. The exothermic reactions increase temperature of coal and bring it to reaction temperature. The rest of the coal is charged from the discharge end. This reacts with CO_2 to produce CO which acts as the reducing agent for Iron Ore. Iron and CO_2 are progressively formed. The rotary kiln is kept at a slant of 5˚-6˚ which causes the materials to flow under gravity.
- The residence time of iron ore inside the kiln is about 10 hours. During this time, iron ore is optimally reduced. Hot sponge iron along with semi burnt coal is discharged at the discharge end. The product stream consists of Fe (4.166 tph), Char (0.554 tph), Ash (2.21 tph) and are discharged at a temperature of 1000˚C.
- After being discharged, the materials enter a rotary cooler where water is sprayed over the cooler and the temperature is brought down to about 120˚C.
- The products, after cooling, need to be separated into Iron, char and other non-magnetic impurities. The iron particles are separated from char and other non-magnetic impurities using electromagnetic separation.
- The products are screened into different sizes and sent to storage. The gases out of the rotary kiln are burnt in a chamber to ensure that CO is negligibly present. Air (3 tph) is fed into the After Burning Chamber to burn the CO gases.

- The gases (25.77 tph), at a temperature of 1000℃, enter the waste heat boiler and then ESP from where they are routed to the stack at a temperature of 200-250℃.
- Dust is separated at ESP at around 1.56 tph.

3.3 AREAS OF INTEREST FOR HEAT INTEGRATION

3.3.1 Rotary Cooler:

Rotary cooler receives hot iron, char etc and cools them indirectly using water from around 1000℃ to about 150℃. This means a temperature drop of around 800-850℃. This heat can be used elsewhere and can cause considerable savings of heat energy. At present, the hot water is simply thrown away which is a big loss.

3.3.2 Stack Gases:

The stack gases consist of mainly CO_2 and air at temperature around 200℃. If the boiler efficiency cannot be improved more, then we can use the stack gas to recover more heat and then release it to the atmosphere.

CHAPTER 4

ENERGY CONSERVATION MEASURES

4.1 POTENTIAL AREAS FOR HEAT INTEGRATION

The two areas where energy is to be conserved are Stack region and Rotary cooler region. The stack gases are released to the atmosphere at a temperature of 230˚C. Usable heat can be extracted and then these gases can be released to the atmosphere at around a temperature of 140-150 ˚C. The rotary cooler employs cooling water at a rate of around 180tph. Water extracts the heat of Products and their temperature is brought down from 1000˚C to 100˚C.

The idea proposed in this project, is to use the hot stack gases to preheat the combustion air fed to the rotary kiln. Currently, combustion air is fed into the rotary kiln at 30˚C. The air temperature has to be increased to the combustion temperature at the expense of extra coal. If the combustion air is preheated before being fed into the kiln an equivalent amount of coal can be saved.

After preheating the combustion air, the stack gases get cooled. These gases can now be used in the rotary cooler region to cool the Products in a direct contact cooler. This will save a lot of water. In this process, the stack gases get heated up and reach a temperature enough to be released to atmosphere. Thus, the proposed system will consist of:

1) A duct to carry the flue gases from Electrostatic Precipitator to Rotary Kiln.
2) An Air-Preheater (Plate type Heat exchanger)
3) A Flue Gas Cooler (Fin-type Exchanger) to reduce the temperature of flue gases.
4) Gas-Solid Heat Exchanger to cool the products using cold flue gas instead of water.
5) A return duct to carry the flue gases back to chimney

4.2 **DESIGN PROCEDURE**

4.2.1 **Duct**

The purpose of the duct is to carry the flue gas from ESP to Rotary Kiln & Cooler. In general, the Mild Steel can be taken as the material of construction of the duct. A suitable diameter is to be selected. As the diameter of the duct increases, the fixed costs (material Cost) increase but the Pressure drop along the duct goes on decreasing and vice versa. This calls a trial & error method. Following procedure was followed to calculate duct diameter.

1) A range of diameters was selected (0.1-2 m).
2) Corresponding velocities and Nre (Reynolds Number), Npr (Prandtl Number) were calculated for each diameter. Details are shown in Table A.1.
3) Film Coefficients for Flue Gas (h_i) & Air (h_o) were calculated & Overall coefficient U_i was calculated for each diameter.
4) The weighted-average U_i was calculated. Details are shown in Table A.2.
5) A range of temperature drops was selected (1-10˚C). Air temperature was assumed to constant at 45˚C.
6) Log-Mean Temperature Difference, Heat Lost, Area and Diameter were calculated for each temperature drop, using the weight-average U_i. Details are shown in Table A.3.
7) For each of the Diameters obtained in step 6, the pressure drop, number of FD Fans, Duct cost, Electricity costs were calculated and the Total Expense was plotted against Diameter. Details are shown in Table A.4.
8) The diameter corresponding to minimum cost was selected. Details are shown in Fig.A.1.

9) The actual heat transfer coefficient was calculated for this diameter and then the corresponding heat loss and outlet temperature calculated. Details are shown in Table A.5.
10) Glass insulation was selected and calculated thickness was applied to restrict the temperature drop in the duct to 1˚C. Details are shown in Table A.6.

4.2.2 Air-Preheater

The purpose of air-preheater is to preheat the combustion air. Air enters the exchanger at temperature of 30 ˚C. Usually Gasketed-Plate Heat Exchangers are used for air Preheaters. HTRI Xchanger Suite 5.0 was used to design the heat exchanger. Following procedure was followed.

1) For a range of temperature drops, the heat duty was calculated for each drop.
2) Keeping a gradient of around 50 ˚C at the hot end, corresponding Heat duty was calculated. Details are shown in Table B.1.
3) Using HTRI Xchanger Suite 5.0, the flow rates of Flue gas & air, the temperature ranges and fouling factors were entered [15].
4) The Plate area, channels/pass, channel spacing and port diameter was adjusted to give results with least percentage of overdesign.
5) The results returned by HTRI Xchanger Suite 5.0 viz. as no. of channels/pass, no. of plates, pressure drop and area were registered. Details are shown in Fig. B.1.

4.2.3 Flue Gas-Water heat exchanger

The purpose of this heat exchanger is to cool the flue-gas to a temperature of 60˚C, so that it can be used in the rotary cooler to cool the hot products. Since the heat transfer coefficient on the gas side is usually less, a Fin-type Shell& tube Heat Exchanger was designed. Waster is used as the cooling medium. HTRI Xchanger Suite 5.0 was used to design the heat exchanger. Following procedure was followed.

1) The allowable outlet temperature for water was selected as 90˚C and the flow rate was calculated. Details are shown in Table C.1.
2) Using HTRI Xchanger Suite 5.0, the flow rates of Flue gas & water, the temperature ranges were entered.
3) The pipe diameter, length, pitch, shell diameter, fin specifications were adjusted to give the least percentage of overdesign.
4) The results returned by HTRI Xchanger Suite 5.0 viz. as no. of tubes, shell diameter, tube diameter, pitch, baffle-spacing, pressure drop and area were registered [12]. Details are shown in Fig.C.1.

4.2.4 Gas-solid heat exchanger

The rotary cooler cools the products using flue gas as the cooling medium. A suitable diameter has to be chosen for adequate heat transfer. Following Procedure was calculated for designing the gas-solid heat exchanger.

1) Heat duty was calculated from energy balances.
2) Design is based upon the amount of heat lost to the surroundings. The fraction of heat lost to surroundings is assumed (based on earlier work). Details are shown in Table D.1.
3) The material (product) conductivity was calculated from material properties [9]. Details are shown in Table D.2.
4) The wall equivalent conductivity was calculated using wall material conductivity & insulation conductivity. Details are shown in Table D.3.

5) For a range of diameters (1.5-4.5m), Ui values were calculated & an average value of Ui was selected. Details are shown in Table D.4.
6) Using the values of LMTD, Heat Load & Ui, area of cooler was calculated.
7) Diameter was calculated using area. Insulation thickness was kept same as current standards. Details are shown in Table D.5.
8) Pressure drop in the exchanger was calculated. Details are shown in Table D.6.

4.2.5 Return Duct

The return duct will carry the flue gases from Gas-Solid heat exchanger to the chimney. The same principles apply to this duct as the first duct. So the diameter of this duct is kept same as the first duct.

4.2.6 Cost Estimation

This consists of capital costs and operating costs.

4.2.6.1 Capital Costs

$$\text{Capital Cost} = \text{cost of } (\text{1st Duct} + \text{Insulation} + \text{AirPreheater} + \text{FlueGas Cooler} + \text{Solid Gas HeatExchanger} + \text{FD Fan} + \text{Return Duct})$$ [11], [16],[17].

$$\text{Annual Fixed Costs} = \frac{\text{Capital Costs}}{\text{Service Life}}$$

4.2.6.2 Operating Costs

$$\text{Annual Operating Cost} = \text{cost of } (\text{Water} + \text{Coal} + \text{WaterPumping} + \text{FanPowerConsumption})$$

4.2.6.3 Annual Savings

$$\text{Annual Savings} = \text{Existing } (\text{Fixed} + \text{Operating})\text{Costs} - \text{New } (\text{Fixed} + \text{Operating})\text{Costs}$$

$$\text{Payback Period} = \frac{\text{New Capital Costs}}{\text{Annual Savings}}$$

CHAPTER 5

RESULTS & DISCUSSION

5.1 DESIGNED EQUIPMENT

The system designed in this project work is shown in the modified Flow sheet Figure 5.1

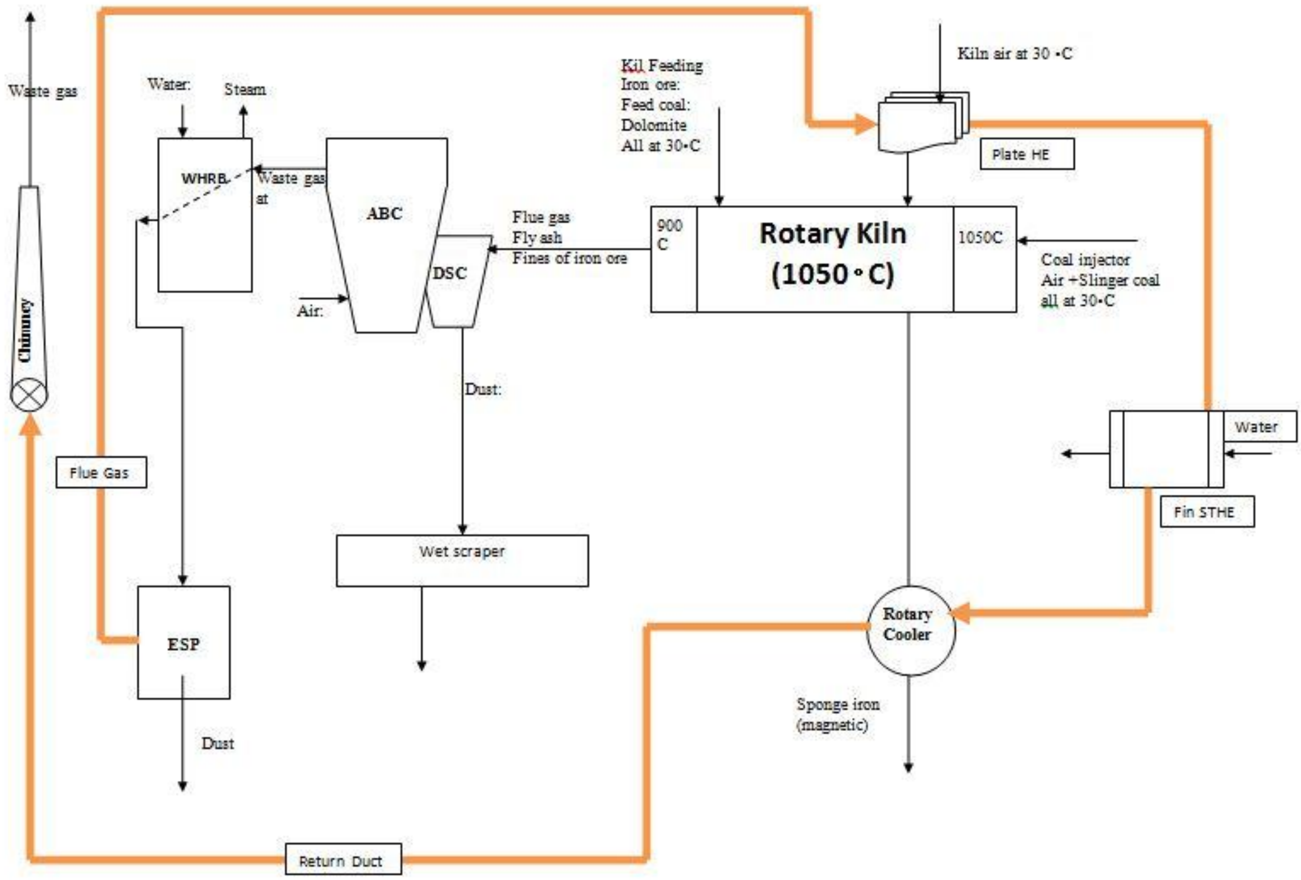

Fig 5.1:- Modified Flow Sheet of SL/RN Process

5.1.1 Duct

The material was selected as mild steel because it is highly heat and corrosion resistant. The distance of stack from rotary kiln is 35 m, hence the length. Wall thickness is usually taken as 8mm, in general [10]. The duct diameter was selected in such a way that only one FD Fan is required to carry the gas through the duct. Any further reduction in diameter will cause a higher pressure drop. This will require more than one FD Fans which increase the Capital costs considerably. The design parameters for the duct is shown in Table 5.1

Table 5.1:- Duct Specification

Parameter	Value/Type	Unit
Material	Mild Steel	-
Diameter	0.309	m
Length	35	m
Wall thickness	8	mm
Pressure drop	51.5	KPa

The annual fixed costs (depreciation of duct and compressor) were plotted against Diameter and the diameter corresponding to the least cost was chosen. The graph is shown in Figure 5.2.

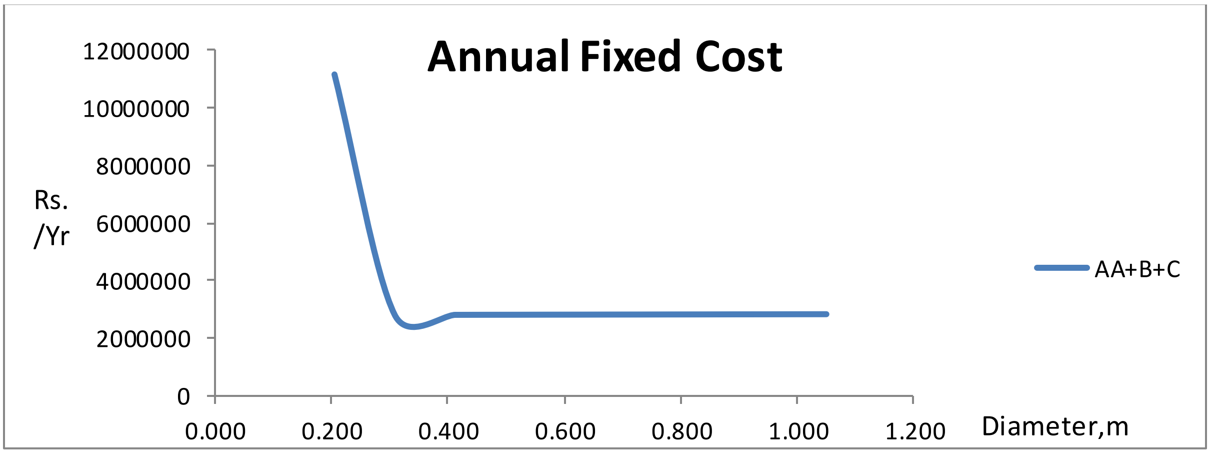

Figure 5.2:- Annual Cost~ Diameter Curve

5.1.2 **Insulation**

The insulation area is same as the surface area of duct to be selected. Glass wool was chosen as the material for insulation because it is suitable for the temperature range of 100-400°C. glass wool has a thermal conductivity of 0.04 W/m^2-K. The thickness was taken as 15.56 mm so as to restrict the temperature drop to 1 degree. Any further loss will cause considerable reduction in coal savings. The specifications of the insulation being provided are shown in Table 5.2.

Table 5.2:- Insulation Specification

Parameter	**Value/Type**	**Unit**
Material	Glass-Wool	-
Area	33.976	m^2
Thickness	15.56	mm

The cost of insulation is so less as compared to coal costs that, even if the insulation costs increase costs increase with increasing thickness, the savings increase at a much higher rate. So, maximum insulation thickness was allowed. The plot of Annual savings against thickness is shown in figure 5.3.

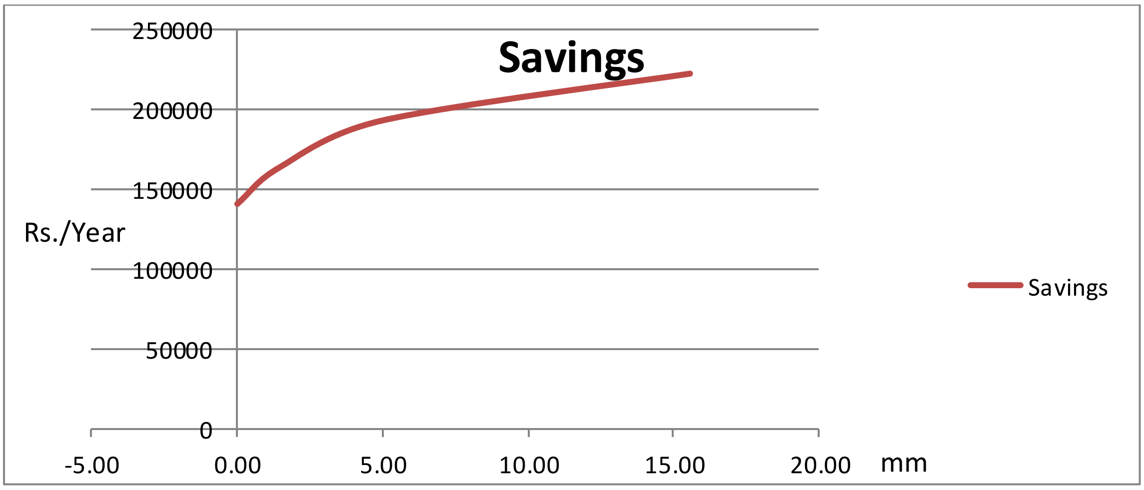

Figure 5.3:- Annual Savings~ Insulation Thickness

5.1.3 **Air-Preheater**

Air preheaters are usually plate type heat exchangers because they give a higher value of heat transfer coefficient. Therefore, Gasketed Plate type exchanger was designed. The area was calculated from heat duty. The no. of channels had to be adjusted to give less pressure drop and simultaneously les overdesign values. Channel spacing and port diameters were adjusted to have lower pressure drops. Chevron angle was adjusted to give higher coefficient. Finally, the area of plate heat exchanger was found to be 61.5 sq.m. by trial and error method using HTRI Xchanger Suite 5.0. The specifications of the Air Preheater have been shown in table 5.3.

Table 5.3:- Air Preheater Specifications

Parameter	Value	Unit
Area	61.5	m^2
Heat Duty	626	KW
Coal Savings	618350	Kg/year
Channels per pass	21	-
No. of Plates	43	-
Channel spacing	10	mm
Chevron Angle	30	degrees
Port Diameter	130	mm
Flue Gas Pressure Drop	33	Kpa

5.1.4 **Flue-Gas Cooler**

The flue gas temperature at the outlet of Air Preheater is 165˚C. The temperature has to be brought down to 60˚C. For this, a fin type heat exchanger was designed. Water at 30˚C was used as the cooling medium. The water outlet temperature was limited to 90 degrees to avoid vaporisation which leads to less coefficient as well as cavitation in the pump. The exchanger was used as fin type to have a higher heat transfer coefficient on shell side. The HTRI Xchanger suite 5.0 was used to design the exchanger with minimum overdesign. The adjustable parameters are Fin specifications, tube OD, pitch, Shell OD etc. Pressure drop was taken care of by adjusting pitch and no. of fins. Finally the area was calculated to be 340 sq.m. The specifications of the Flue Gas Cooler are shown in table 5.4.

Table 5.4:- Flue Gas Cooler Specification

Parameter	Value	Unit
Type	1-1	Pass
Area	340	m^2
No. of Tubes	255	-
Shell ID	712	mm
Tube OD	25.4	mm
Tube Wall Thickness	0.711	mm
Tube Length	4.877	m
Pitch	35	mm
No. of Fins	20	-
Fin thickness	0.8	mm
Fin height	5	mm
Flue-Gas Pressure Drop	3.18	KPa
Water Pressure Drop	4.836	Kpa

5.1.5 **Solid-Gas Heat Exchanger**

In the Solid-Gas Heat Exchanger, the insulation thickness and material have been kept same as existing insulation. Material selected was mild steel. This was chosen because the existing rotary coolers in typical sponge iron plants are made of mild steel. Wall thickness, in general, was taken to be 8mm. Heat duty was calculated to be 996 KW. The fraction of heat lost was calculated to be 160 KW (16%). The conductivity of material was calculated to be 0.953 KW using parallel thermal resistance method. Average coefficient was taken to be 3.18 W/sq.m K by taking average of a range of values. The area required was calculated to be around 150 sq.m. The L/D ratio was kept, in general, equal to 40/3. This way the diameter was calculated to be 1.7 m and length to be 28m. Refractory material and thickness was kept same as the existing coolers. Flue gas outlet temperature was calculated using energy balance. The specifications of the solid-gas heat exchanger are shown in table 5.5.

Table 5.5:- Solid-Gas Heat Exchanger Specifications

Parameter	Value/Type	Unit
Material of wall	Mild Steel	-
Length	28	m
Inner Diameter	1.7	m
Wall Thickness	8	mm
Refractory Material	Whytheat-C	-
Refractory Thickness	192	mm
Pressure Drop	0.03	KPa
Flue Gas Outlet Temperature	140	˚C

5.1.6 **Return Duct**

The return duct was designed on the same principles as the first insulated duct. The specifications of the return duct are given in table 5.6.

Table 5.6:- Return Duct Specifications

Parameter	Value/Type	Unit
Material	Mild Steel	-
Diameter	0.309	m
Length	35	m
Wall thickness	8	mm
Pressure drop	51.5	KPa

5.2 COST ESTIMATION

5.2.1 Capital Cost Estimation

Capital cost was found by adding the cost of the proposed equipment. The duct costs were calculated by calculating the weight of material required and multiplying with price per unit weight. The insulation volume, density and weight were calculated and the insulation price was determined by multiplying with price per unit weight. Air-Preheater and Flue Gas cooler costs were determined by comparing with plots of Area against Cost [10], [11]. The Solid-Gas heat exchanger cost was found by adding the material cost and refractory cost. The FD Fan cost was found by referring to manufacturer's manual [4]. The total capital cost is shown in table 5.7.

Table 5.7:- Capital Cost Estimation

Equipment	Cost (Rs)
1ST Duct & Return Duct	144540
Insulation	1485
Air Preheater	630420
Flue-Gas Cooler	4977000
Solid-Gas Heat Exchanger	318080
Refractory Cost	1722700
FD Fan	9500000
Total	1, 72, 94, 220 (Appx.)
Annual Fixed Cost (A)	17, 29, 422 (Appx)

5.2.2 Operating Cost Estimation

Operating cost consists of cost of coal, water and electricity. The new coal consumption was found out by subtracting the annual coal savings (equivalent to heat duty of Air Preheater) from current coal consumption. The water cost is calculated by using the water consumption data in the Flue Gas cooler. The FD Fan electricity cost is determined by the rating of the fan [4]. The annual operating costs, under the proposed system, are shown in table 5.8.

Table 5.8:- Operating Cost Estimation

Head	Cost(Rs/year)
Coal cost	58349130
Water Cost	775720
Water Pumping Cost	16045
FD Fan Electricity Cost	1840410
Annual Operating Costs (B)	60981300 (Apprx.)

5.2.3 Total Annual Cost

Total Annual cost = A+B = **1729422+60981300= Rs.62710720 (C)**

5.2.4 Existing Capital Cost

For the existing system, the cost of rotary cooler and refractory cost is added, and the capital cost is shown in table 5.9.

Table 5.9:- Existing Capital Cost Estimation

Equipment	Cost(Rs.)
Rotary Cooler	400940
Refractory Cost	2171470
Total Capital Cost	2572406
Annual Fixed Cost (A”)	257240

5.2.5 **Existing Operating Cost**

The existing operating cost is based on the current consumption of coal, water and cost of pumping water. The pump rating was taken from practical plant data and the operating cost was calculated. Table 5.10 shows the existing Operating costs.

Table 5.10:-Existing Operating Cost

Head	Cost(Rs/year)
Coal cost	59895000
Water Cost	9198420
Water Pumping Cost	1415700
Annual Operating Costs (B”)	70509120 (Apprx.)

5.2.6 **Existing Total Annual Cost**

Total Existing Annual cost = A”+B” = **257240 + 70509120= 70766360 (C”)**

5.2.7 **Annual Savings**

Annual savings = B-B” = Rs.95,27,820/-

Total Capital Cost= Rs. 1,72,94,217/-

Payback Period= 1.81 years

Amount of coal savings = 618350 kg

Amount of water savings = 1,183,903 tons

CHAPTER 6

CONCLUSIONS

In the present work waste heat recovery system is designed to integrate the heat of waste gas in the sponge iron production process. The salient features of the study are as follows:

1) The instalment of the above system requires a capital cost of approximately Rs.173 lakh.

2) The major components contributing to the annual savings are Coal and water. The annual Coal savings was calculated to be 618350 kg which amounts to Rs. 15.5 lakh. The annual water savings was calculated to be 11.8 million tons which amounts to Rs. 83 lakh. Total annual savings was calculated to be Rs.95.3 lakh.

3) With these annual savings, the Payback Period was calculated to be 1.81 years.

The advantage of this system is that it utilises the waste heat trapped in the stack gases and simultaneously reduces the water consumption by a considerable amount. Unlike older waste heat recovery systems (waste heat boilers etc), it does not require much higher temperatures. The system solves the purpose of extracting heat from low quality sources. After the flue gases pass through the Gas-Solid Heat Exchanger, they attain a temperature of around 140˚C which is sufficient to lower their density and raise them upwards.

Therefore, it is concluded that this system can be applied to sponge iron plants.

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APPENDIX A

DESIGN OF DUCT

The physical properties of the Flue gas are shown in Table A.1.

Table A.1:- Physical Properties of Flue Gas

Density of Flue gas =	0.946	Kg/m^3
Viscosity of flue gas=	0.000	Pa.s
Thermal conductivity of flue gas =	0.031	W/m-K
Specific heat of Flue gas=	1660.000	J/kg-K
Npr =	1.152	

The weighted-average value of U has been calculated by considering a range of diameters. The calculation of average U has been shown in Table A.2.

Table A.2:- Calculation of average U

Diameter	CS Area	Viscocity	FG Flow	Nre	Npr	Nu	hi	ho	U	U*D
(m)	(sq.m)	(Pa.s)	(kg/h)	(G*D/μ)	(Cp*μ)/k		(W/ m^2K)	(W/ m^2K)		
0.1	0.008	2.180E-05	25770	4180859	1.152	4778	1500.217	10	9.916	0.992
0.2	0.031	2.180E-05	25770	2090430	1.152	2744	430.824	10	9.756	1.951
0.3	0.071	2.180E-05	25770	1393620	1.152	1984	207.652	10	9.524	2.857
0.4	0.126	2.180E-05	25770	1045215	1.152	1576	123.722	10	9.237	3.695
0.5	0.196	2.180E-05	25770	836172	1.152	1318	82.796	10	8.908	4.454
0.6	0.283	2.180E-05	25770	696810	1.152	1139	59.632	10	8.551	5.131
0.7	0.385	2.180E-05	25770	597266	1.152	1007	45.183	10	8.176	5.723
0.8	0.503	2.180E-05	25770	522607	1.152	905	35.530	10	7.793	6.234
0.9	0.636	2.180E-05	25770	464540	1.152	824	28.742	10	7.409	6.668
1.0	0.785	2.180E-05	25770	418086	1.152	757	23.777	10	7.031	7.031
1.1	0.950	2.180E-05	25770	380078	1.152	702	20.028	10	6.662	7.328
1.2	1.131	2.180E-05	25770	348405	1.152	654	17.125	10	6.306	7.568
1.3	1.327	2.180E-05	25770	321605	1.152	614	14.827	10	5.966	7.756
1.4	1.539	2.180E-05	25770	298633	1.152	579	12.975	10	5.642	7.899
1.5	1.767	2.180E-05	25770	278724	1.152	547	11.460	10	5.335	8.003
1.6	2.011	2.180E-05	25770	261304	1.152	520	10.203	10	5.046	8.073
1.7	2.270	2.180E-05	25770	245933	1.152	495	9.148	10	4.774	8.115
1.8	2.545	2.180E-05	25770	232270	1.152	473	8.254	10	4.518	8.133
1.9	2.835	2.180E-05	25770	220045	1.152	453	7.489	10	4.279	8.130
2.0	3.142	2.180E-05	25770	209043	1.152	435	6.828	10	4.055	8.109
20.0										114.353
									Average U=	5.718

The value of diameter has been calculated for each pressure drop and shown in table A.3.

Table A.3:- Diameter Calculation

Inlet Temp	Drop allowed	Outlet Temp	Heat Loss	U	LMTD	Area	Length	Diameter	Velocity
(C)	(C)	(C)	(KW)	W/m^2 K		m^2	m	m	(m/s)
230	1	229	11.883	5.720	184.500	11.260	35	0.102	2698.212
230	2	228	23.766	5.720	183.998	22.581	35	0.205	670.892
230	**3**	**227**	**35.649**	**5.720**	**183.496**	**33.964**	**35**	**0.309**	**296.549**
230	4	226	47.531	5.720	182.993	45.410	35	0.413	165.895
230	5	225	59.414	5.720	182.489	56.919	35	0.518	105.589
230	6	224	71.297	5.720	181.984	68.493	35	0.623	72.920
230	7	223	83.180	5.720	181.478	80.131	35	0.729	53.276
230	8	222	95.063	5.720	180.971	91.835	35	0.835	40.562
230	9	221	106.946	5.720	180.463	103.605	35	0.942	31.869
230	10	220	118.828	5.720	179.954	115.442	35	1.050	25.669

For each diameter, pressure drop, FD Fan requirement and Net expenses have been calculated and shown in Table A.4.

Table A.4:- Net Expenses

Diameter	ΔP (KPa)	FD Fans Reqd	Electricity(AA)	Duct Cost	Annual Dep(B)	Maintainance (BB)	Fan Costs	Annual dep(C)	NET EXPENSES3
m			Rs/year(39 kw)	Rs	Rs/Year	Rs/year	Rs	Rs/year	AA+B+BB+C
0.102	10313.296	104		23950	2395	1197			
0.205	365.411	4	7361640	48030	4803	2402	38000000	3800000	11168845
0.309	**51.504**	**1**	**1840410**	**72243**	**7224**	**3612**	**9500000**	**950000**	**2801246**
0.413	12.777	1	1840410	96589	9659	4829	9500000	950000	2804898
0.518	4.320	1	1840410	121069	12107	6053	9500000	950000	2808570
0.623	1.777	1	1840410	145686	14569	7284	9500000	950000	2812263
0.729	0.837	1	1840410	170441	17044	8522	9500000	950000	2815976
0.835	0.435	1	1840410	195336	19534	9767	9500000	950000	2819710
0.942	0.244	1	1840410	220371	22037	11019	9500000	950000	2823466

The net expenses were plotted against diameter and the graph is shown in fig A.1.

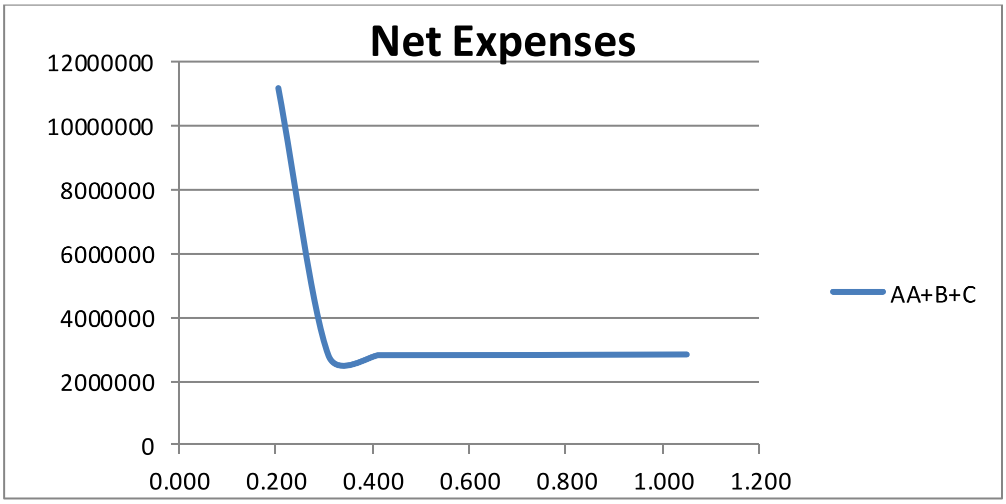


Figure A.1:- Net Expenses ~ Diameter Plot

The lowest diameter was selected and actual U and outlet temperature were calculated. The calculations have been shown in table A.5.

Table A.5:- Actual U & Outlet Temperature

Diameter =	0.309	m
Nre =	1353519.8	
viscosity =	0.0000218	Pa.s
Specific Heat capacity =	1660	j/kg-K
Thermal conductivity =	0.03	W/m-K
Npr=	1.15	
Nu =	1938.40	
hi=	26.01	W/sq.m-K
Air coefficient, ho =	10	W/sq.m-K
Pipe wall thickness, Xw=	0.008	m
Pipe material =	mild steel	
Kms=	45	W/sq-m-K
Insulation conductivity =	0.04	W/m-K
U=	7.21	
Theoritical Heat Lost =	35.6485	KW
Assumed U=	5.72	
Actual U=	7.21	
Actual Heat Lost =	44.96	KW
Inlet Temp=	230	C
Temp Drop	3.78	C
Outlet Temp =	226.22	C

The insulation thickness was calculated for different temperature drops and the values are shown in table A.6.

Table A.6:- Insulation Thickness ~ Temp Drop

Inlet Temp	Drop allowed	Outlet Temp	LMTD	Area(inside)	heat lost	New Ui	Old Ui	Insulation (x)	Insulation
(C)	(C)	(C)	(C)	(sq.m)	(KW)	(W/sq.m-K)	(W/sq.m-K)	m	mm
230	3.78	226.22	183.103	33.976	44.917	7.220	7.220	0.0000	0.00
230	3	227	183.496	33.976	35.649	5.718	7.220	0.0015	1.46
230	2	228	183.998	33.976	23.766	3.802	7.220	0.0050	4.98
230	1	229	184.500	33.976	11.883	1.896	7.220	**0.0156**	**15.56**

For each insulation thickness, cost and net savings were calculated and the values are presented in table A.7.

Table A.7:- Net Savings ~ Thickness

Insulation	insulation volume	weight	Price	Annual Depr.	Total annual fixed cost	Heat Savings	Annual Savings	Coal Saved	Cost saved	Net Savings
mm	cu.m	kg	(rs)	(rs)	rs	KW	KJ	Kg	rs	Rs
0.00	0.000	0.00	0	0	0	56.919	1487632109	56223.199	140558	140558
1.46	0.049	1.98	138	14	15	66.188	1729876500	65378.523	163446	163432
4.98	0.169	6.77	474	47	50	78.070	2040446232	77116.119	192790	192741
15.56	**0.529**	**21.15**	**1480**	**148**	**155**	**89.953**	**2351015964**	**88853.714**	**222134**	**221979**

APPENDIX B

DESIGN OF AIR PREHEATER

For different values of flue gas temperature drops, the outlet temperature of air was calculated and the values are shown in Table B.1.

Table B.1:- Air Outlet Temperature

Inlet Flue T	Outlet Flue T	m*Cp (flue)	Inlet Air T	m*Cp (Air)	Outlet Air T
229	65	11.88283333	30	5	419.7569333
229	70	11.88283333	30	5	407.8741
229	75	11.88283333	30	5	395.9912667
229	80	11.88283333	30	5	384.1084333
229	85	11.88283333	30	5	372.2256
229	90	11.88283333	30	5	360.3427667
229	95	11.88283333	30	5	348.4599333
229	100	11.88283333	30	5	336.5771
229	105	11.88283333	30	5	324.6942667
229	110	11.88283333	30	5	312.8114333
229	115	11.88283333	30	5	300.9286
229	120	11.88283333	30	5	289.0457667
229	125	11.88283333	30	5	277.1629333
229	130	11.88283333	30	5	265.2801
229	135	11.88283333	30	5	253.3972667
229	140	11.88283333	30	5	241.5144333
229	145	11.88283333	30	5	229.6316
229	150	11.88283333	30	5	217.7487667
229	155	11.88283333	30	5	205.8659333
229	160	11.88283333	30	5	193.9831

229	**165**	**11.88283333**	**30**	**5**	**182.1002667**
229	170	11.88283333	30	5	170.2174333
229	175	11.88283333	30	5	158.3346

The output of the HTRI Xchanger Suite 5.0 is presented in Figure B.1.

See Data Check Messages Report for Warning Messages.
See Runtime Message Report for Warning Messages.

Process Conditions		Hotside		Coldside	
Fluid name		Flue Gas		Air	
Flow rate	(kg/s)		7.158		5.000
Temperature, Inlet/Outlet	(Deg C)	229.00	165.00	30.00	182.10
Weight fraction vapor, Inlet/Outlet	(--)	1.00	1.00	1.00	1.00
Temperature, Average/Skin	(Deg C)	197.00	169.00	106.05	165.55
Pressure, Inlet/Average	(kPa)	100.001	83.514	100.001	92.351
Pressure drop, Total/Allow	(kPa)	32.975	50.001	15.302	50.001
Nominal channel velocity	(m/s)		51.88		31.74
Fouling resistance	(m2-K/W)		0.00000		0.00000
Equivalent shear stress	(kPa)		0.093		0.042
Maldistribution parameter	(--)		7.84		7.49

Exchanger Performance

Hot film coefficient	(W/m2-K)	303.15	Actual U	(W/m2-K)	125.407
Cold film coefficient	(W/m2-K)	215.40	Required U	(W/m2-K)	124.165
Hot regime		Sens. Gas	Duty	(MegaWatts)	0.626
Cold regime		Sens. Gas	Area	(m2)	61.500
EMTD	(Deg C)	81.9	Overdesign	(%)	1.00

Unit Geometry			Pack Configuration	
Units in series/parallel	(--)	1 / 1	Group #	1
No. of passes, hot/cold	(--)	1 / 1	Plate Type 1	1
Total plates/channels	(--)	43 / 42	Plate Type 2	1
Flow configuration	(--)	Countercurrent	Channels	21
Inlet port locations	(--)	Same Side	Hot pass #	1
Flow path	(--)	Diagonal	Cold pass #	1
Hot inlet flow direction	(--)	Upflow	Channel (Per pass)	21

Plate Geometry			Plate Type 1		
Channel width	(mm)	842.70	Manufacturer	(--)	
Channel spacing	(mm)	10.000	Plate ID	(--)	
Equivalent diameter	(mm)	17.094	Chevron angle	(deg)	30.00
Average plate pitch	(mm)	10.600			
Port diameter	(mm)	130.00	**Plate Type 2**		
Tightened pack length	(mm)	445.80	Manufacturer	(--)	
Horizontal port c-c	(mm)	700.00	Plate ID	(--)	
Vertical port c-c	(mm)		Chevron angle	(deg)	

Port Velocities, m/s			Pressure Drop, % of Total			Thermal Resistance, %	
	Hot	Cold		Hot	Cold	Hot side	41.39
Inlet	730.77	327.63	Channel	103.5	102.0	Cold side	58.20
Outlet	637.55	492.26	Other	-3.5	-2.0	Fouling	0.00
						Metal	0.41

Figure B.1:- Software Output for Air Preheater

APPENDIX C

DESIGN OF FLUE-GAS COOLER

In the flue gas cooler, keeping the outlet temperature of water to be 90 degrees, the mass rate of water was calculated. The calculation is shown in Table C.1.

Table C.1:- Mass & Energy Balance in Flue gas cooler

Mass rate of FG	7.158333	Kg/sec
Specific heat	1.66	KJ/kg
Temperature Drop	105	degrees
Water del T	60	degrees
specific heat	4.18	KJ/kg
Mass rate of Water=	4.97487	

Using the above mass rate, the Flue gas cooler was designed using HTRI Xchanger Suite 5.0 and the output is shown in Figure C.1.

HTRI	**Output Summary** Released to the following HTRI Member Company: *nit* *sam*	Page 1

Xist E Ver. 5.00 09-05-2011 05:02 SN: Friendsl **SI Units**

Design - Horizontal Countercurrent Flow TEMA AES Shell

See Data Check Messages Report for Warning Messages.
See Runtime Message Report for Warning Messages.

Process Conditions		Hot Shellside		Cold Tubeside	
Fluid name		flue gas		water	
Flow rate	(kg/s)		7.1580		4.9800
Inlet/Outlet Y	(Wt. frac vap.)	1.000	1.000	0.000	0.000
Inlet/Outlet T	(Deg C)	165.00	60.00	30.00	90.00
Inlet P/Avg	(kPa)	100.001	98.412	0.000	0.000
dP/Allow.	(kPa)	3.179	0.000	4.836	0.000
Fouling	(m2-K/W)		0.000176		0.000000

Exchanger Performance

Shell h	(W/m2-K)	105.98	Actual U	(W/m2-K)	59.01
Tube h	(W/m2-K)	514.90	Required U	(W/m2-K)	58.84
Hot regime	(--)	Sens. Gas	Duty	(MegaWatts)	0.9921
Cold regime	(--)	Sens. Liquid	Area	(m2)	340.702
EMTD	(Deg C)	49.5	Overdesign	(%)	0.29

Shell Geometry			Baffle Geometry		
TEMA type	(--)	AES	Baffle type	(--)	None
Shell ID	(mm)	711.201	Baffle cut	(Pct Dia.)	
Series	(--)	1	Baffle orientation	(--)	
Parallel	(--)	1	Central spacing	(mm)	4775.23
Orientation	(deg)	0.00	Crosspasses	(--)	1

Tube Geometry			Nozzles		
Tube type	(--)	Longitudinal Fin	Shell inlet	(mm)	590.551
Tube OD	(mm)	25.400	Shell outlet	(mm)	590.551
Length	(m)	4.877	Inlet height	(mm)	24.301
Pitch ratio	(--)	1.3937	Outlet height	(mm)	24.300
Layout	(deg)	90	Tube inlet	(mm)	52.553
Tubecount	(--)	255	Tube outlet	(mm)	52.553
Tube Pass	(--)	1			

Thermal Resistance, %		Velocities, m/s		Flow Fractions	
Shell	55.69	Shellside	12.78	A	
Tube	42.56	Tubeside	4.379e-2	B	0.834
Fouling	1.04	Crossflow	0.00	C	0.166
Metal	0.713	Window	0.00	E	
				F	

Fig.C.1:- Software Output for Flue Gas Cooler

APPENDIX D

DESIGN OF SOLID-GAS HEAT EXCHANGER

The heat duty of the Solid-Gas heat exchanger was calculated and the values are shown in Table D.1.

Table D.1:- Heat & Mass balance in solid gas heat exchanger

Mass flow rate of Iron=	4.166	tph
Mass flow rate of Char=	0.554	tph
Mass flow rate of Ash=	2.21	tph
Total mass flow rate of solid products from kiln = Fe + Char + Ash =	6.93	tph
Inlet temperature of Solid materials =	1020	℃
Outlet temperature of Solid materials=	110	℃
specific heat capacity of Iron=	0.46	kJ/kg-K
specific heat capacity of char(charcoal)=	1	kJ/kg-K
specific heat capacity of ash(60%silica+40%alumina)=	0.664	kJ/kg-K
AVERAGE SPECIFIC HEAT CAPACITY of solid materials=(Σ mass-fraction*specific heat)	0.568225	kJ/kg-K
Heat lost from solid materials=m.Cp.dT=	**995.3883**	**kW**
Assuming Fraction heat loss to surroundings =	0.16	(Based on earlier reports)
So heat lost to the surroundings =	**159.2621**	**kW**
(This amount of heat is lost to the surroundings from the product		

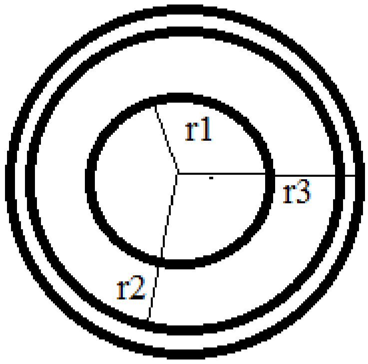
The thermal conductivity of the mixture of materials was calculated and the values are presented in Table D.2.

Table D.2:- Calculation of Conductivity

The material consists of Iron, Char & Ash
Since the materials are mixed up, we can consider their thermal resistance to be parallel
$\Rightarrow \frac{1}{R} = \left(\frac{1}{R1}\right) + (\frac{1}{R2}) + (\frac{1}{R3})$ $\Rightarrow \frac{kA}{x} = \frac{k1 * A1}{x1} + \frac{k2 * A2}{x2} + \frac{k3 * A3}{x3}$
in parallel resistances case, the lengths travelled are equal through all the resistances
$\Rightarrow x = x1 = x2 = x3$ $\Rightarrow k = \frac{k1 * A1}{A} + \frac{k2 * A2}{A} + \frac{k3 * A3}{A}$
The ratio of Areas can be cosidered equal to mass fractions
$\frac{A1}{A} = 0.6\ (iron)$ $\frac{A2}{A} = 0.08 (char)$ $\frac{A3}{A} = 0.32 (ash)$
k1 = 60
k2=0.97
k3=0.55
putting these values, we get the value of material conductivity
k= 36.25 W/m.K

The equivalent conductivity of the wall and refractory was calculated and the values are presented in Table D.3.

Table D.3:- Equivalent wall conductivity



General wall thickness of ducts and coolers =	0.008	m
Thickness of refractory material =	0.192	m
$r2 = r1 + 0.192$ $r3 = r1 + 0.2$		
R(equivalent) = R(Wall) + R(refractory)		
$\left(\frac{x}{keq * Al}\right) = \left(\frac{xwall}{kwall * Alwall}\right) + \left(\frac{xrefractory}{krefractory * Alrefractory}\right)$		
Usually for coolers and driers, (outer radius / inner radius) < 1.4		
so A(log-mean) = A(arithmetic mean)		
putting the values in the relation, we get		
$\left(\frac{0.2}{keq * 2\pi L(r1 + r3)}\right) = \left(\frac{0.008}{45 * 2\pi L(r2 + r3)}\right) + \left(\frac{0.192}{0.918 * 2\pi L(r1 + r2)}\right)$		
$keq = \frac{0.2}{(2r1 + 0.2) * [\frac{0.209}{2r1 + 0.192} + \frac{0.000178}{2r1 + 0.392}]}$		
General range of inner radius	1-1.5	m
Equivalent conductivity of wall, Keq =	**0.953**	**W/m.K**

Using a range of diameter, an average coefficient U was calculated and the values are shown in table D.4.

Table D.4:- Average Coefficient

k=thermal conductivity				
w=wall (mild steel+refractory)			Di	Ui
m= (material inside cooler)			1.5	3.520612
ho = Heat transfer coefficient of air			2	3.326211
			2.5	3.188254
The relation between coefficients is			3	3.079668
$\left(\frac{1}{Ui}\right) = \left(\frac{1}{ho}\right) * \left(\frac{Di}{Do}\right) + \left(\frac{xw}{kw}\right) * \left(\frac{Di}{Dl}\right) + \left(\frac{xm}{km}\right)$			3.5	2.988712
			4	2.909437
			4.5	2.838485
putting all the values , we get the following relation				
$\frac{1}{Ui} = \frac{Di}{76} + \frac{Di}{10(Di+0.4)} + \frac{0.2Di}{0.953(Di+0.2)}$				

Using the value of average coefficient Ui, the area requirement was calculated. Keeping the ratio of Length to Diameter as 40/3, the diameter and length were calculated and the values are shown in table D.5.

Table D.5:- Diameter and Length of Solid-Gas Heat Exchanger

Heat loss to surroundings, q=	159262.1	W
LMTD =	336	K
Heat transfer coefficient = Ui =	3.18	W/m2K
$q = Ui * Ai * LMTD$		
putting all values and solving the equations, we get		
Area, Ai =	149.0548255	m2
Ai = π*Di*L =	149.0548255	m2
For Rotary drum coolers and dryers, L/Do = 40/3		
Solving for this, we get		
Di =	**1.7**	**m**
Do=	**2.1**	**m**
Length = L =	**28**	**m**

The pressure drop in the duct was calculated and the values are presented in table D.6.

Table D.6:- Pressure Drop in Gas-solid Exchanger

Equivalent Dia, Deq=	1.24	m
Flow Area=	1.70235	sq.m
Velocity=	13.0538	m/sec
Nre=	239182	
f=	0.00386	
delP=	**29.7342**	**Pa**